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Engineering The Future

Introduction

To advance our knowledge of the solar system, identifying and developing technologies that enable human exploration and improve efficiency of human explorers through the use of robotic systems is of primary importance. There are a number of areas – physical and functional – where development of human-exploration robotics is recommended. Physically, robotic systems will be integral to orbital systems as well as planetary missions; functionally, robotic systems will be involved in the infrastructure that allows human exploration as well as the science investigations that drive them.

In orbital systems, robotic systems can aid in construction and maintenance as well as provide assistance for space flights, improving the safety and productivity of the crew. Telerobotic systems like the Flight Telerobotic Servicer (originally designed for Space Station Freedom) would serve well here. Honeybee Robotics has worked extensively with teams trying to improve the performance and reliability of these types of telerobotic systems. We have found that the most improvement/advancement has come with careful, task-oriented design of end effectors. This approach to robotic design leverages the effort invested in the design of interchangeable end-effectors for specific functions of the overall system and greatly simplifies telerobotic systems. These 'smart' end effectors can reduce the complexity of control systems as well as reducing the amount of training and system/task-specific knowledge an operator requires. To facilitate the simple and successful change-out of these end-effectors, an effort to design reliable and robust connectors that allow the transfer of data and power is needed.

For planetary systems, robotic systems will be essential in carrying out preparations for human explorers such as reconnaissance for identifying suitable locations for bases and construction and maintenance of facilities. When human exploration is underway, robotic systems can contribute greatly by assisting in scientific studies, greatly reducing risk and increasing science yield of missions.

Much research to achieve these ends has been done at Honeybee Robotics and is detailed below.

Infrastructure-driven Robotic Systems

Development of technologies enabling infrastructure construction and maintenance in extraterrestrial and space environments has been initiated for a number of previous missions. Interchangeable task-oriented end-effectors, connectors and docking mechanisms have been a focus of Honeybee design work.

One such system is the FTS Gripper developed initially for Space Station Freedom. The FTS Gripper, designed for NASA by Honeybee Robotics, allowed a telerobotic arm such as FTS (Flight Telerobotic Servicer) to manipulate specific objects. (Figure 1) Its 'fingers' are easily changed out for any number of task-specific end pieces.

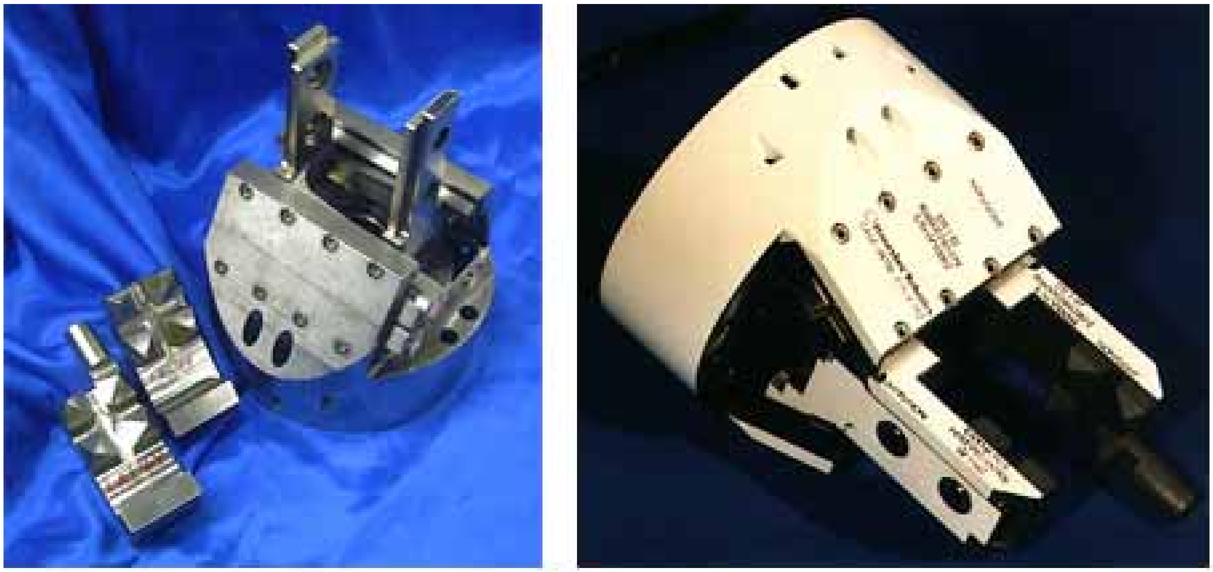

Figure 1: FTS Gripping End Effector breadboard (left) and final prototype (right)

Another such technology is The Langley Research Center End-Effector (LaRC EE) used for installation of strut members in large space truss structures. (Figure 2) Designed to be compatible with 1" Langley joints, this end-effector will allow the assembly of precision, doubly-curved truss structures. End-effectors of this kind are specialized tools that are capable of the complete installation and removal of varying length struts, including locking the joint connector. The end-effector must also be capable of removing and inserting the struts into storage trays for delivery to the assembly site. An on-board machine vision system is used to position the LaRC EE. The design is scalable for struts of much longer or shorter lengths and avoids the use of pneumatic equipment entirely.

Connector technologies include a robotic docking device intended for use on space station or other large orbiting platforms. The Robotic On-Orbit Worksite Attachment Mechanism/Worksite Attachment Fixture (WAM/WAF) mechanism was also originally designed for the Flight Telerobotic Servicer (FTS). (Figure 3)

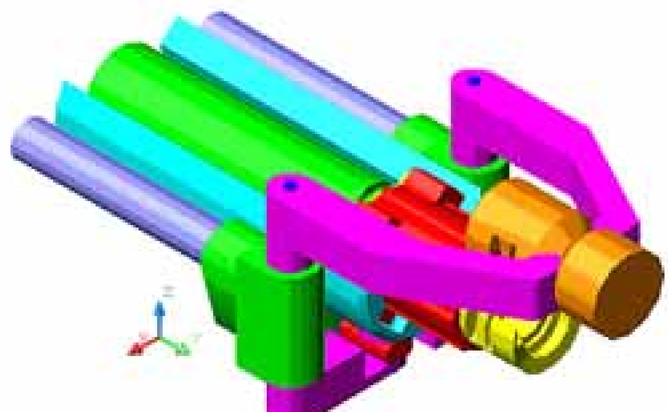

Figure 2: LaRC Truss Assembly End-Effector

Figure 3: WAM (left) and WAF (right). The two halves engage using a kinematic clamp technique. Dust cover protects the three electrical connectors.

Figure 4: WAM (left) and WAF (right).

Figure 5: Application of the WAM / WAF attached to the corner of ORU. The key feature of the fastening system is its required ability to fully mate with the platform site before disengagement with the robotic arm. This provides fault tolerance for inadvertent release.

The Robotic Orbital Retrieval Unit (ORU) Fastening System built upon the previously-tested WAM/WAF technology, and was specifically designed for astronaut EVA as well as robotic use. (Figures 4 & 5) The fastening system provides both mechanical and electrical connection from robot to ORU to platform.

In 1993, Honeybee developed an end-effector to aid EVA for Hubble Space Telescope repair and maintenance. (Figure 6) This particular end-effector engaged a toolbox latch, released the locking mechanism and then opened the toolbox door to allow access by astronauts.

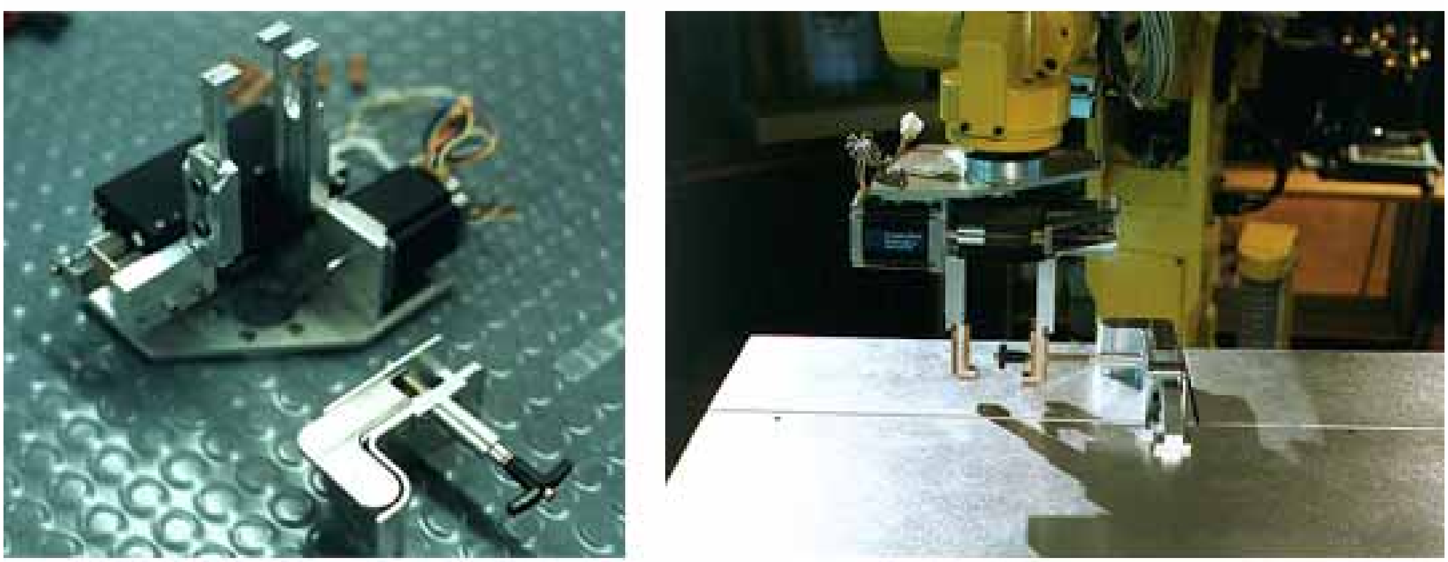

Figure 6: HST EE prototype (left); HST toolbox end-effctor engaging toolbox latch (right)

Science-driven Robotic Systems

Human scientific studies can be greatly enhanced by robotic systems designed to perform specific tasks autonomously – tasks that require high precision and need to be performed many times. They improve the efficiency of human explorers, working when humans are acclimatizing, sleeping or involved in other activities. Additionally, these robotic systems can ensure pristine material samples for scientific study as well as reduce risk of biohazard exposure to human explorers.

Numerous robotic sample acquisition systems have been highly developed at Honeybee for various sample return missions previously and currently undertaken by NASA. Leveraging this substantial store of knowledge and experience in remote science studies, Honeybee foresees these autonomous and semi-autonomous systems as indispensable aides to human explorers.

MiniCorer

The miniature rock coring and rock core acquisition and transfer system (Mini-Corer) was designed as a part of the Athena investigation. (Figure 7) Its major function was to acquire rock cores for in-situ examination by other instruments and to provide for precision caching of the acquired cores for sample return.

The Mini-Corer is a highly developed robotic drill capable of obtaining two 25-mm long and 8-mm diameter cores from the same hole from very strong rocks. The low power Mini-Corer can readily drill 25 mm into strong basalt in less than 6 minutes while consuming under 10 W-hr of power. A breakthrough feature of the Mini-Corer is its unique ability to break off the core from the base rock and retain the core. A pushrod, internal to the core tube, provides controlled and positive ejection of the core.

The Mini-Corer can be mounted on positional axes such as a pitch or translation axis. The additional axes in conjunction with the z-axis of the Mini-Corer can be called upon to position the tip of the Mini-Corer to a core storage location (cache) or to a convenient position for examination of the core tip by the instrument heads mounted elsewhere.

Mini-Corer sensor data, required for the drilling algorithm, generates a signature that correlates with physical characteristics of the target rock. Torque, thrust and penetration rate data can be inverted and compared to drill performance in terrestrial analogs to infer rock compressive strength and density. Thus the robotic tool itself provides diagnostic data that adds to the overall science output of the mission.

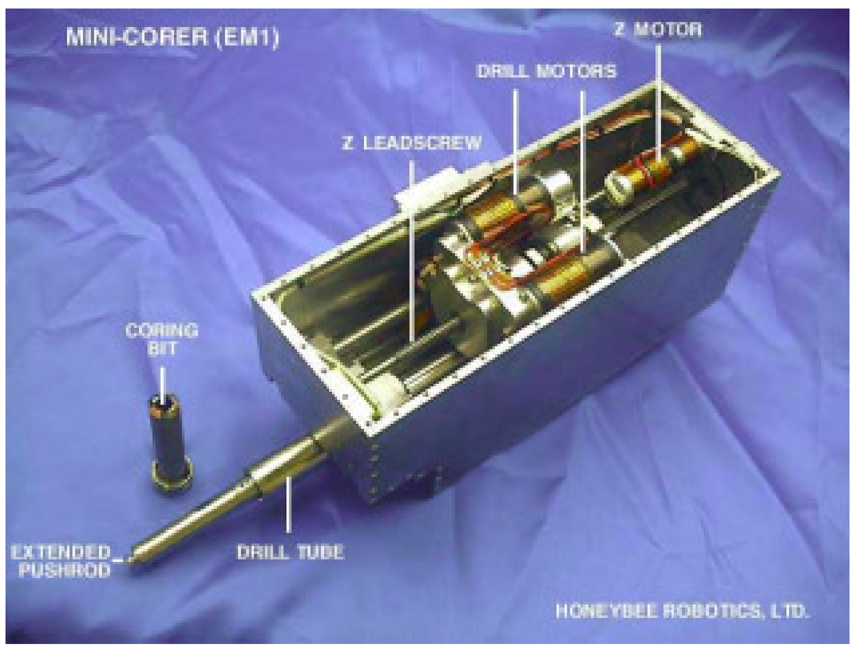

Figure 7: Mini-Corer autonomous sample acquisition and handling system

A 5 mm breadboard version of the Mini-Corer had been successfully field tested aboard JPL's FIDO rover and the 8 mm Athena Mini-Corer was very close to being flight ready when the 2003 Mars Sample Return Mission was cancelled.

SATM

The Sample Acquisition and Transfer Mechanism (SATM) is a highly developed robotic sampling system that can provide the necessary interfaces with in-situ science instruments and sample return containers. (Figure 8) This autonomous and precise handling of samples adds great value to human exploration missions by giving the human explorers the time to perform the functions that *only* humans do well

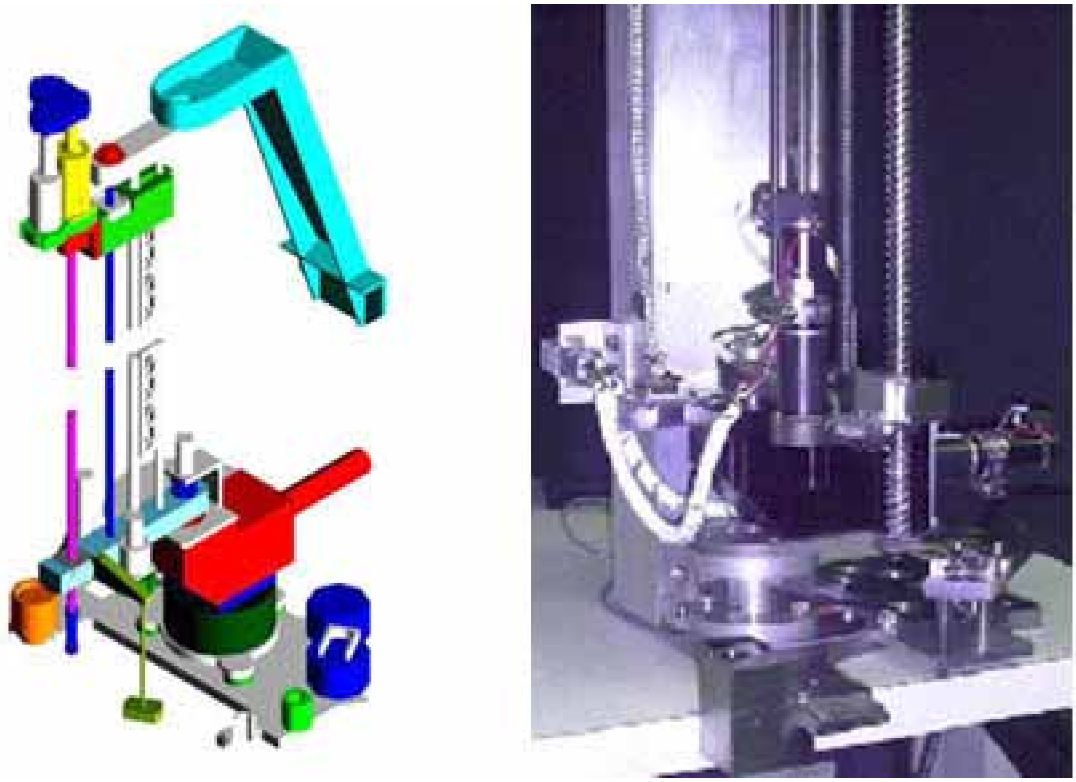

Figure 8: Sample Acquisition and Transfer Mechanism

The 1.2 meter SATM was developed and successfully tested at Honeybee Robotics to demonstrate the performance requirements necessary to meet the ST/4 Champollion mission goals. Since the ST/4 cancellation, JPL has supported the rework of the SATM (now TRL 6) to meet Mars drilling and sample acquisition goals.

Currently, scaling of the SATM to 10-20 meters is underway. This multifunctional sampling tool would use the proven SATM drilling and sample handling technology with a drill string feeder to allow for deeper drilling and integrate Mini-Corer core acquisition technology.

The SATM can autonomously:

- Acquire surface and subsurface, unconsolidated and consolidated samples of very high compressive strengths. All samples are acquired and transported without cross contamination.
- Transport and transfer samples to instruments such as a microscope/IR spectrometer, chemical analysis ovens, or to sample return containers located at the base of the SATM.
- Positively eject a sample within its sample chamber to ensure that samples are delivered to in-situ instruments.
- Operate in low gravity environment with low thrust reaction. Reaction thresholds are adjustable in controls software.

Additionally, the SATM features:

- A sapphire window through which the samples in the chamber can be presented for analysis to a microscope
- A drill tip that can be used as a tool to open and close the sample return container, eliminating the need for a separate mechanism.
- A control system with feedback sensors, adjustable threshold limits for current, torque and thrust. The controls system can be enhanced with real-time adaptive algorithms that would optimize the use of power and time depending on conditions encountered at the drill site.

Multifunctional Robotic Systems

Simple bit change-outs for drilling systems allow a variety of tasks to be performed by one robotic tool.

The Mini-Corer, for instance, was designed with quick-change bit acquisition capability. Using the z, break-off and push rod axes, the current bit is removed from the Mini-Corer tip and a new drill bit is acquired in a make-before-break robotic transfer. This allows for multiple bits with varying functions to be used interchangeably, dramatically increasing the functionality of this robotic system.

Employing the quick-change subsystem used for changing drill bits, the Mini-Corer drill can acquire a soil acquisition end-effector. (Figure 9) This gripper utilizes the pushrod and drill drive train for its operation; no additional actuators are required. Should it be desired, the Mini-Corer can also acquire a rock abrasion tool to grind away the surface rind of rock, and allow examination of fresh rock by human explorers and/or in-situ instruments.

These robotic systems can easily be integrated into rovers (as is being proposed for upcoming MSR missions) that may serve initially as reconnaissance robots and then used repeatedly as human explorers expand their survey of planets. (Figure 10)

Figure 9: Regolith sampling end effector

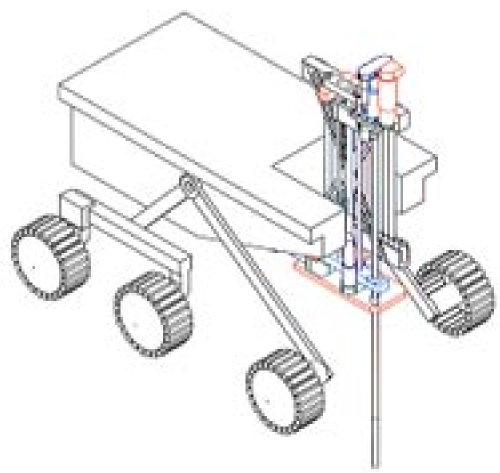

Figure 10: Mini-Corer testing on prototype rover (left); Autonomous, deep-drilling SATM deployed on a rover (right)

With the autonomous acquisition of specialized tools and the ability to choose which tools are appropriate for particular situations, robotic systems of this kind will become indispensable to human exploration of planetary bodies.

Integrated Systems

A large advantage of robotics developed with human exploration as a goal is their ability to function in a number of capacities. While categorizing systems in terms of their main functions (science & infrastructure) is convenient; in practice, integrating their capabilities may well yield superior results. For example, the Excavator is a telerobotic rover that may function as a trench-digging machine that simultaneously performs subsurface analysis as well as precision sample acquisition and transfer. (Figure 11)

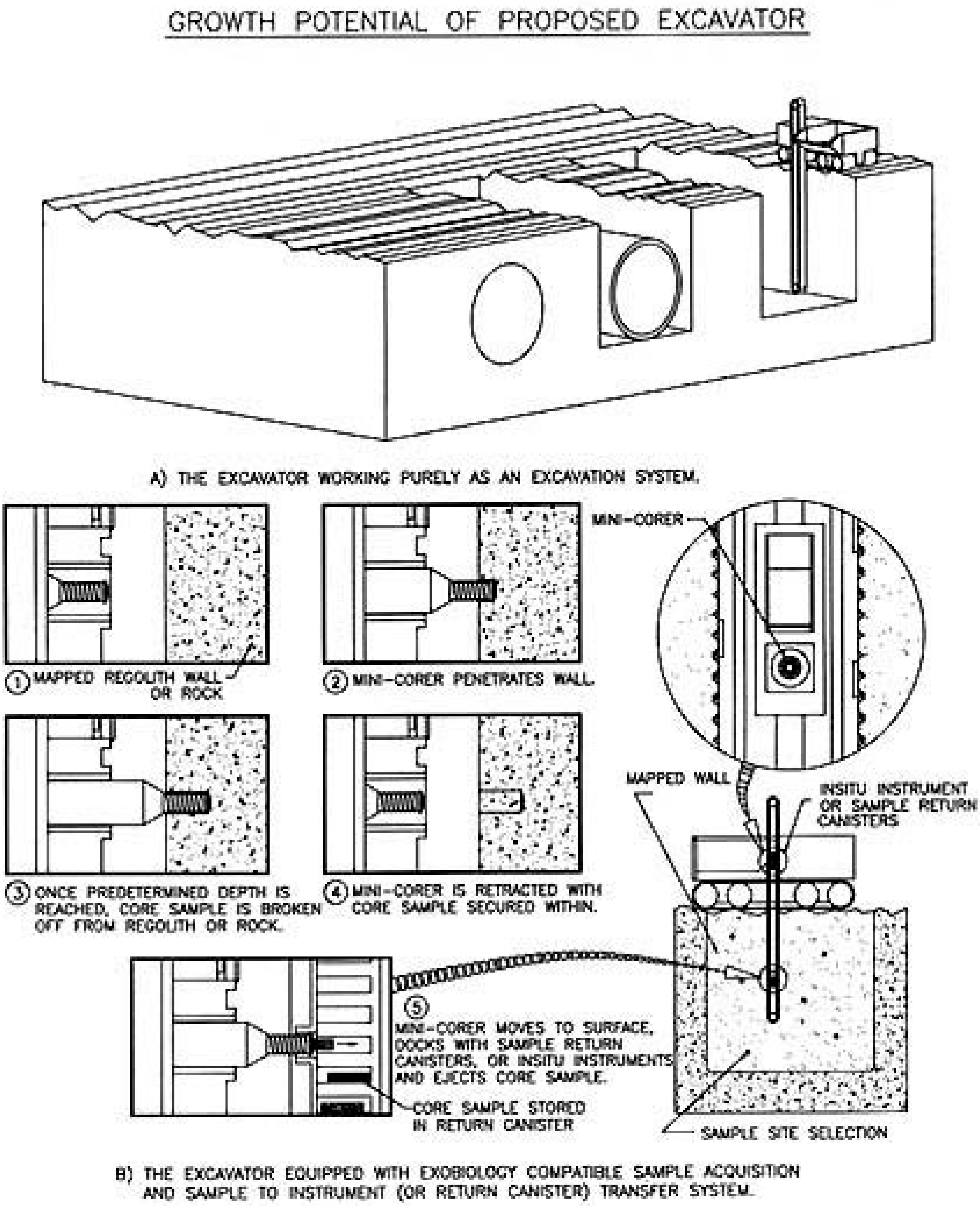

Figure 10: Multi-functional Robotic Excavator

Conclusions

Honeybee Robotics has an extensive heritage in the development of unique robotic systems designed to facilitate human exploration of the Solar System; we recommend:

- Directing design efforts to task-oriented end-effectors will significantly simplify robotic systems. (FTS Gripper, LaRC Truss End-Effector)
- Interchangeable, task-oriented end-effectors allows a less complex robotic system that can handle a multitude of tasks while avoiding high levels of training and system-specific skills for operators. (WAM/WAF, ORU Fastening System, MiniCorer Scooper/RAT)
- Leveraging the extensive design efforts that have gone into remote science studies of extraterrestrial bodies, science-driven robotic systems will be indispensable aides to human explorers, reducing (biohazard/exposure) risk to human explorers and increasing science yield of missions - working when humans are acclimatizing, sleeping or involved in other activities - and ensuring the collection and study of pristine samples. (MiniCorer, SATM)
- Robotic systems that integrate infrastructure-related functions with scientific study capabilities may increase cost-effectiveness of human exploration in the Solar System. (Excavator)

Select Relevant NASA Contracts:

"**Fastener for Telerobotics & Manual Servicing of Small & Medium-Sized Payloads**" Contract #NAS5-32813: awarded in 1995 from Goddard Space Flight Center

"**Variable-Torque Clutch Brake for On-Orbit Robotic and Other Mechanisms**," Contract #NAS5-32508: awarded in 1993 from the Goddard Space Flight Center

"**A Gravity Compensation System for Simulation of On-Orbit Telerobotic Operations**," Contract #NAS5-31391: awarded in 1990 by the NASA Goddard Space Flight Center

"**Variable-Torque Clutch/Brake for On-Orbit Robotic and Other Mechanisms**", Contract #NAS5-31881: awarded in 1991 by the NASA Goddard Space Flight Center

"**A Cableless Joint**", Contract #NAS5-32423: awarded in 1992 from NASA Goddard Space Flight Center

"**A Vibration-Resistant Telerobotic/EVA Astronaut-Compatible Fastener for Small/Medium-Sized Payloads**", Contract #NAS5-38022: awarded in 1993 from the NASA Goddard Space Flight Center

"**A Compact Ultrasonic Multi Degree-of-Freedom Positioning System**", Contract #NAS5-32723: awarded in 1994 from the NASA Goddard Space Flight Center

"**A Miniature Planetary Subsurface Sample Acquisition and Sample Return System**", Contract #NAS8-40703: awarded in 1996 from the NASA Jet Propulsion Laboratory (contractually administered by MSFC)

"**Subsurface Coring Sampler System**", Contract #NAS3-01067: awarded in 2001 by NASA JPL (administered by Glenn Research Center)

"**Variable-Torque Clutch Brake for On-Orbit Robotic and Other Mechanisms**," Contract #NAS5-32508: awarded in 1993 from the NASA Goddard Space Flight Center

"**Geared Flex Rings; A Cableless Joint Technology**," Contract #NAS5-38071: awarded in 1994 from the NASA Goddard Space Flight Center

"**Fastener for Telerobotics & Manual Servicing of Small & Medium-Sized Payloads**", Contract #NAS5-32813: awarded in 1995 from The NASA Goddard Space Flight Center

"**Miniature Planetary Subsurface Sample Acquisition and Sample Return System**", Contract #NAS8-97034: awarded in 1996 from NASA Jet Propulsion Laboratory (contractually administered by MSFC)

"**The Touch and Go Surface Sampler**," Contract #NAS2-01068: awarded in 2001 by NASA Ames Research Center

"Preliminary Design and Development of the Champollion Web Docking System" — Contract #961264: awarded 1/8/98 by NASA Jet Propulsion Laboratory

"Deep Space 4 / Champollion Sample Acquisition & Transfer Mechanism (SATM) Prototype" — Contract #961337: awarded 4/6/98 by NASA Jet Propulsion Laboratory

"The Small Body and Planetary Sample Acquisition & Transfer Mechanism (SATM) Technology Development" — Contract #1203240: awarded 11/5/99 byNASA Jet Propulsion Laboratory

"Rock Abrasion Tools (RATs) for Mars Exploration Rover (MER) Mission" — Contract #1223932: awarded 12/1/00 by NASA Jet Propulsion Laboratory

"Fabrication of a Robot End Effector for Installation of Strut Members in Large Precision Space Truss Structures" — Contract #L-70785D: awarded 6/20/01 by NASA Langley Research Center